Quantitative Evaluation of a Real-Time Non-rigid Registration of a Parametric Model of the Aorta for a VR-Based Catheterization Guidance System

P. Fontanilla-Arranz[1], B. Rodriguez-Vila[1], H. Fontenelle[2], J. Tarjuelo-Gutiérrez[1], O.J. Elle[2,3], and E.J. Gómez[1]

[1] Bioengineering and Telemedicine Centre, ETSI de Telecomunicación, Universidad Politécnica de Madrid, Madrid, España
{pfontanilla,brvila,egomez}@gbt.tfo.upm.es
[2] The Intervention Center, Oslo University Hospital, Oslo, Norway
hugues.fontenelle@rr-research.no
[3] Department of Informatics, University of Oslo, Oslo, Norway
oelle@ous-hf.no

Abstract—**This work presents a real time non-rigid registration method for a parametric model of the aorta based on computer animation techniques. The endovascular system is modeled as a polygonal mesh and a skeletal structure, both calculated automatically from segmented pre-operative images. The skeleton, registered using linear regression methods, supports an adaptive triangular mesh, both adapting in real time to the longitudinal deformations and changes affecting the aorta during the procedure. These changes are offered to the surgeon as part of a virtual-reality catheterization guidance system. The initial evaluation shows that the algorithm and implementation are able to handle up to 5 situation updates per second while maintaining a mean registration error of 1,012 mm and a maximum of 4.346 mm, thus effectively supporting real-time navigation.**

Keywords—**Catheterization, navigation, virtual-reality, non-rigid registration, real-time.**

I. INTRODUCTION

A catheter is medical devices that can be inserted in the body to treat diseases or perform a surgical procedure. Catheterization refers to the use of or insertion of a catheter into a body cavity, duct, or vessel for cardiovascular, urological, gastrointestinal, neurovascular, or ophthalmic applications. In this paper we focus on aortic catheterization, for example for the deployment of a stent, balloon or valve in the descending aorta, although the method is readily applicable for other procedures.

The goal of a catheterization guidance system is to provide the surgeon with a updated navigable 3D vision with the tools and anatomic structures present in an aortic catheterization: the catheter, the aorta and its branches.

A key component of these systems is the registration algorithm [1], which calculates the geometrical relation between the pre- and intraoperative images. The quality of the registration is fundamental for the correct positioning of the catheter as well as precise navigation.

There are two basic approaches to the registration problem: rigid registration algorithms, used for affine transformation in static structures, and non-rigid algorithms, used in deformable structures such as organic tissue [2].

Registration methods used in projects such as ARIS*ER [3] are of the rigid kind, and therefore limited to non-dynamic structures, such as the brain or the bones.

However, the aorta suffers two classes of motions and deformations during a catheterization, due to the heart beats, respiratory movements and the catheter insertion itself. These are longitudinal (modifying the medial line of the artery) and transversal distortions, mainly due to an asymmetric pulsatile distension of the artery.

All these changes must be reflected in the aorta model by means of a complete registration, which provides a reliable, up-to-date image of the current vessel configuration. In this work a non-rigid, real-time approach to the modeling of the longitudinal deformations is presented.

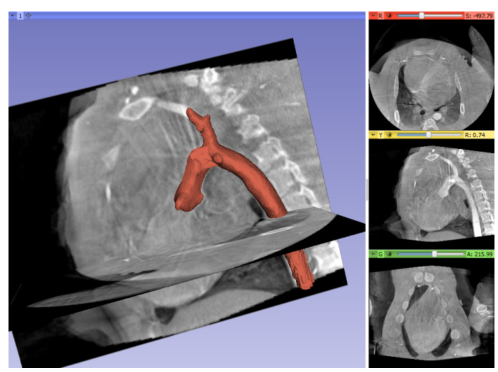

Fig. 1 Axial, sagittal and coronal views of the DynaCT of the pig, and 3D model of the segmented lumen.

II. MATERIALS

This research work is integrated into the SCATh platform, which is a virtual reality (VR) based platform aimed to minimize the ionizing radiation during the catheter navigation in aortic catheterization.

The images used for the evaluation of the method were obtained in the angio-room at the Intervention Center, Oslo University Hospital, Oslo, Norway during different stages of a vascular intervention using a porcine model. Three different

L.M. Roa Romero (ed.), *XIII Mediterranean Conference on Medical and Biological Engineering and Computing 2013*,
IFMBE Proceedings 41,
DOI: 10.1007/978-3-319-00846-2_14, © Springer International Publishing Switzerland 2014

DynaCT (cone-beam computed tomography) with contrast, acquired with breath-hold in mid-phase, were selected. The lumen of the aorta was segmented in each DynaCT using the open-source Slicer 4 software [5] (see Figure 1).

III. METHODOLOGY

From the patient pre-operative images to the deformable model, the proposed methodology follows the steps depicted in Figure 2:

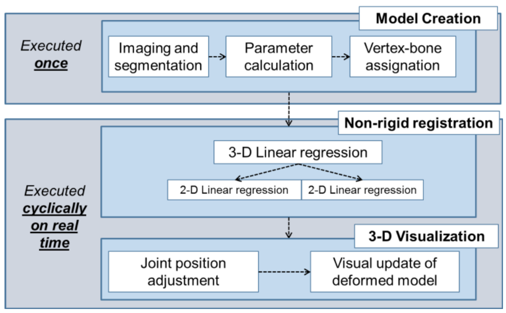

Fig. 2 Workflow, from MRI to deformed model

A. *Model Creation*

The aorta model is based on the computer animation technique named skeletal animation [6], normally used to represent vertebrate characters. The model is composed by two parts: the *skin*, a polygonal surface which represents the exterior of the model; and the *skeleton*, a set of straight lines (bones) which approximate the centerline of the volume. Figure 3 presents an example of the skeleton (blue line) and the mesh (pink surface) of one of the models used.

The model is loaded in a graphical engine [7], which will be in charge of rendering it and executing the deformations and changes that take place during the intervention. This animation is only valid to represent longitudinal changes in the aorta, which are the ones modeled.

The following characteristics of skeletal animation have direct influence in the registration algorithm:

- The tessellated surface (skin) is attached to the skeleton in a process called skinning. Each vertex of the polygon set is assigned to one or more bones. This assignation is then used by the graphical engine to know which vertices should be affected when the skeleton is modified.
- The skeleton is a hierarchical chain of straight segments, called bones, calculated from the centerline of the segmented images. The point where two bones are linked is called *joint*.

The full process of the model creation is explained in detail in [8].

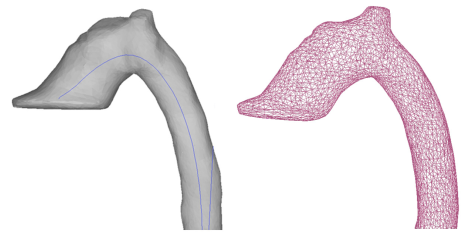

Fig. 3 Left: full model with skeleton in blue. Right: Mesh of the model.

B. *Non-rigid Registration*

The objective of the non-rigid registration process is to adjust the model configuration to the intraoperative information received during the procedure.

The intraoperative aorta centerlines are sent to the registration algorithm as series of 3-D points, samples of the interpolated curve. The full skeleton is updated by iteratively finding the position for each bone that best fits the provided discrete curve.

The registration process is composed of two phases: (1) determining the samples of the intraoperative curve that must be fitted by each bone and (2) finding the best position for that bone.

1. Bone-sample assignation

The link joining each bone of the model's skeleton to his *parent* (the joint) is fixed, and should the parent bone move, the child bone is forced to move along to maintain the union. In addition, the length of the bones must not be changed during the model manipulation, or the skin will not be properly updated afterwards, causing visual glitches. Therefore, as one end of the bone is fixed by its father and the length is constant, the only task needed to adjust the whole bone position is to find the optimal location for the other end.

Each bone will be able to fit a certain amount of samples, limited again by its length and its link to the parent joint. During the model creation, the bones are created as long as possible, but always under a user-set maximum length parameter. Therefore, in this step the bone is placed so that the maximum number of samples fit under it. Once this set of points is determined, the optimal location for the bone can be calculated in the next step.

2. 3-D Linear Regression

The bone-samples set is, under certain restrictions, akin to a set of discrete points and a (limited) straight line. From a mathematical standpoint, the problem of fitting the bone to the samples can be approached as a 3-D linear regression.

The presented modified algorithm is performed as two 2-D linear regressions in cascade. On broad terms, it involves

the following: first obtaining the 2-D linear fitting of 2 dimensions of the data set (X and Y), and then using the projection of the solution line and the remaining coordinate (Z) to perform another 2-D linear fitting. This will provide the director cosines of the straight line that is oriented as the fitted bone should be. Measuring from the proximal end (a point found as the distal end of the previous bone, by the same procedure) a distance equal to the current bone length, the final position for the distal end of the current bone is set.

As a result, the bone is fitted, providing in turn one fixed point for the next bone to be repositioned. This process is performed sequentially for each bone, eventually updating the whole skeleton. Once the new position for every bone has been found, the graphical engine must be informed so it can apply the appropriate deformation to the skin: the positions of the joints are set to the new ones, and the engine is ordered to update the model. This calculates new positions for all the vertices, providing the updated aspect of the model which will follow the registered skeleton.

The Hausdorff distance, a standard metric for evaluating distances between meshes [9], has been used to evaluate the non-rigid registration performance.

IV. Results and discussion

For this assessment, an offline registration of the porcine aorta models was implemented. The 3D models shown in Figure 4 represent different moments of the same intervention, and therefore different states of deformation. Each of these models was registered against the other two, providing six registrations in total. For each model, its centerline was extracted, and then used as the target centerline for the other two models. In this way, it is tested that a model of any state of the patient aorta is deformable to represent other states that the vessel will undergo during the intervention.

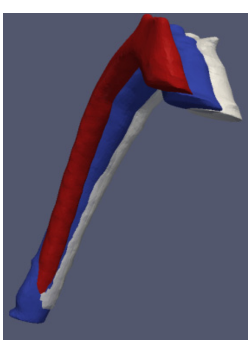

Fig. 4 Models of 3 different stages of the porcine aorta during the intervention.

One of the registrations is shown in Figure 5. The "patient-specific" preoperative 3D model of the aorta is shown using two orthogonal views: from the right side (left column) and from the anterior side (right column).The upper row shows the 3D model in its original shape, while the lower row presents the deformed model using the new registered skeleton. The old centerline (pink spheres) and the new centerline (yellow spheres) are shown to facilitate the visualization of the changes introduced during the procedure.

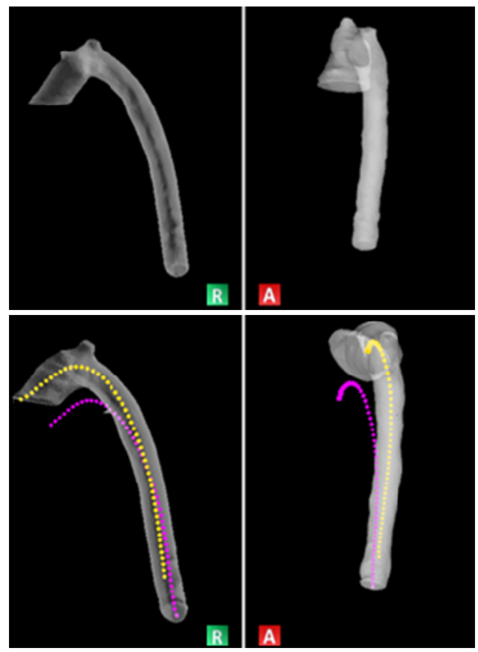

Fig. 5 Top, preoperative model before registration. Bottom, preoperative (blue) model after being fitted to the centerline of the red model. Previous centerline shown in pink, registered centerline shown in yellow

For these models, composed of up to 50 bones (joints and links), and using centerlines divided in 300 samples, the registration takes less than 100 ms on a desktop computer, enough to be considered as real-time. However, currently, the new centerline is extracted from a DynaCT, an intra-operative image which takes 8 seconds. As a consequence, this centerline extraction remains the main bottleneck of the process for real-time purposes.

The results from the quantitative evaluation are shown in Table 1 . The average mean error for the 6 cases is slightly over 1 mm, while the maximum error is around 5 mm in the worst case.

Table 1 Hausdorff distance values for the 6 registrations, in millimeters.

	Minimum	Maximum	Mean	Std dev
A to B	0,0021	5,3671	0,7698	1,0135
A to C	0,0031	3,3108	1,0155	0,6179
B to A	0,0037	2,7507	0,5138	0,4282
B to C	0,0004	5,1530	1,2096	0,7787
C to A	0,0062	4,6630	1,3581	0,9235
C to B	0,0048	4,8333	1,2072	0,8612
Average	0,0034	4,3463	1,0123	0,7705

Figure 5 represents these results, overlaying the error values over the 3D volumes. It seems to the authors that the registration values are below 1 mm except in certain regions: the lower part of the descending aorta and ascending aorta, and around the brachyocephalic artery. These errors may be due to the original segmentation differences, and excluding these regions the registration is excellent.

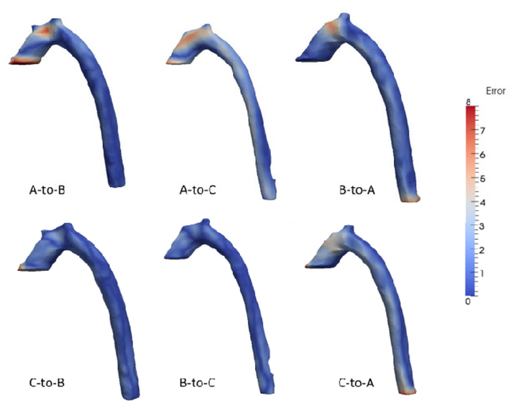

Fig. 6 Graphical representation of the Hausdorff distance over the 3D geometrical model

V. Conclusions

This work presents a non-rigid registration method suitable for real-time navigation. The quantitative evaluation of the method shows that the modeling of the longitudinal deformations is enough for a correct matching of simple anatomies like the aorta, obtaining a great improvement compared to the use of a rigid registration method.

This registration approach is integrated into the SCATh platform, a catheterization navigation platform based on virtual reality. The updated deformed state of the models allows the surgeon to know the exact position of the tracked catheter inside the vessel, potentially increasing the effectiveness and safety of the catheterization procedures.

Future works involve the centerline extraction using intraoperative information, such as intra-vascular imaging and real-time sensing. In addition, more complex models can be created, modeling the outward arteries with additional branches in the skeleton. We propose that this will reduce the registration error for bifurcation areas such as the top of the arch.

Acknowledgment

The authors gratefully acknowledge the financial support of the European Commission under the 7th Framework Programme in the frame of project SCATh, FP7-ICT-2009-4-248782. They also would like to thank A. Dore, S.Lin and V. Meiser and F.Gaya for their help and advice.

References

1. Intracardiac echo-guided image integration: optimizing strategies for registration. T.S. Fhamy, H. Mlcochova, O.M. Wazni, et al. 2007, J Cardiovasc Electrophysiology, págs. 18:276-82.
2. J.B.A.Maintz, M. ,. (1998). A survey of medical image registration vol 2, Nº 1 . Medical Image Analysis, 1-37.
3. ARIS*ER consortium, project main page. Retrieved February 2013 from http://www.ariser.info/
4. Sette, M., E.V. Poorten, J. Vander Sloten, A. Dore, B. Rodriguez-Vila, H. Fontenelle, D.M. Pierce, G. Leo, M. Vatteroni and V. Meiser, Smart Catheterization Project, The Virtual Physiological Human Conference(VPH 2012), London, England, September 18{20, 2012.
5. Fedorov A., Beichel R., Kalpathy-Cramer J., Finet J., Fillion-Robin J-C., Pujol S., Bauer C., Jennings D., Fennessy F., Sonka M., Buatti J., Aylward S.R., Miller J.V., Pieper S., Kikinis R. 3D Slicer as an Image Computing Platform for the Quantitative Imaging Network. Magn Reson Imaging. 2012 Nov;30(9):1323-41. PMID: 22770690.
6. Real-time 3D Character Animation with Visual C++. Lever, N. (2002). Focal Press.
7. Irrlicht documentation. (s.f.). Retrieved 12th November 2011, from http://irrlicht.sourceforge.net/docu/
8. Automatic generation of real-time deformable parametric model of the aorta for a VR-based catheterism guidance system. P. Fontanilla Arranz, B. Rodríguez Vila, P. Sánchez-González,E.J.Gómez Aguilera, A. Dore, M. Sette, J. Vander Sloten. Int J CARS Proceedings (2012) 7 (Suppl 1): S 161-162
9. Mesh: Measuring errors between surfaces using the Hausdorff distance. Aspert, Nicolas, Diego Santa-Cruz, and Touradj Ebrahimi. Multimedia and Expo, 2002. ICME'02. Proceedings. 2002 IEEE International Conference on. Vol. 1. IEEE, 2002.